

Review on heavy-ion physics

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(ricevuto l'8 Ottobre 2010; pubblicato online il 28 Gennaio 2011)

Summary. — Collisions of heavy ions (nuclei) at ultra-relativistic energies ($\sqrt{s_{NN}} \gg 10$ GeV per nucleon-nucleon collision in the centre of mass system) are regarded as a unique tool to produce in the laboratory a high-energy density and high-temperature state of strongly-interacting matter. In this short review, we will discuss the expected features of this hot and dense state, describe indications on its properties emerged from the experimental programs at the CERN-SPS and BNL-RHIC accelerators, and finally outlook the perspectives for the forthcoming heavy-ion runs at the CERN-LHC.

PACS 12.38.Mh – Quark-gluon plasma.

PACS 25.75.Nq – Quark deconfinement, quark-gluon plasma production and phase transitions.

1. – Introduction: phenomenology of hot and dense QCD matter

On the basis of thermodynamical considerations and of QCD calculations, strongly interacting matter is expected to exist in different states. Its behaviour, as a function of the baryonic chemical potential μ_B (a measure of the baryonic density) and of the temperature T , is displayed in the phase diagram reported in fig. 1 (left). At low temperatures and for $\mu_B \simeq m_p \simeq 940$ MeV, we have ordinary matter. When the energy density ε of the system is increased, by “compression” (towards the right) or by “heating” (upward), a phase transition is predicted: the density of partons (quarks and gluons) becomes so high that the confinement of coloured quarks in colourless hadrons vanishes and a deconfined Quark-Gluon Plasma (QGP) is formed.

From a theoretical point of view, the phase diagram can be explored within the framework of lattice QCD [1, 2], although calculations are limited to cases of null or small μ_B . The phase transition is identified by a large increase of the energy density $\varepsilon(T)$ when the temperature T reaches the critical value $T_c = (175 \pm 15)$ MeV [2]. Considering that the energy density of an equilibrated ideal gas of particles with n_{dof} degrees of freedom is $\varepsilon = n_{\text{dof}} \frac{\pi^2}{30} T^4$, the dramatic increase of ε/T^4 at T_c can be interpreted as due to the change of n_{dof} from 3 in the pion gas phase to 37 (with 2 quark flavours) in the deconfined

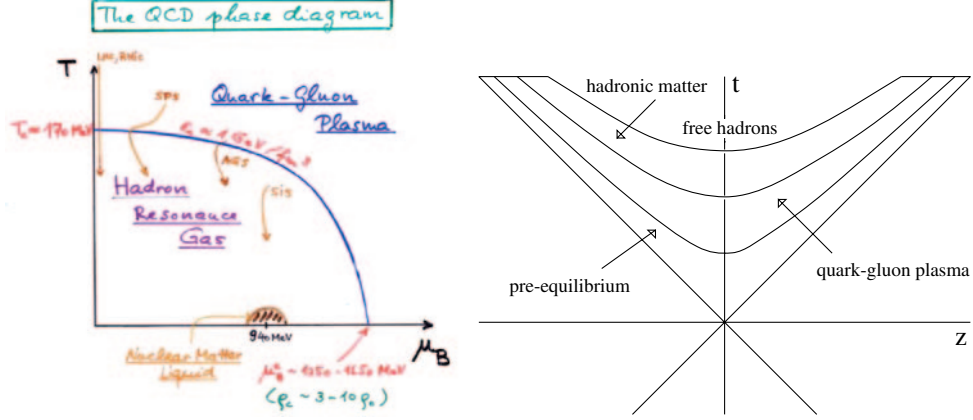


Fig. 1. – Left: phase diagram of QCD matter [3]. Right: the expected evolution of a high-energy nuclear collision.

phase, where the additional colour and quark flavour degrees of freedom are available⁽¹⁾. The energy density for a QGP at T_c is $\varepsilon_c \approx 1 \text{ GeV/fm}^3$.

In heavy-ion collisions, both temperature and density increase, possibly bringing the system to the phase transition. In the diagram in fig. 1 (left) the paths estimated for the fixed-target (SIS $\sqrt{s_{NN}} \simeq 1$ GeV, AGS $\sqrt{s_{NN}} \simeq 5$ GeV, SPS $\sqrt{s_{NN}} \simeq 17$ GeV) and collider (RHIC $\sqrt{s_{NN}} = 200$ GeV, LHC $\sqrt{s_{NN}} = 2.75-5.5$ TeV) experiments are shown. The evolution of a high-energy nucleus-nucleus collision is usually pictured in the form shown in fig. 1 (right). After a rather short equilibration time $\tau_0 \simeq 0.1-1 \text{ fm}/c$, the presence of a thermalized medium is assumed, and for sufficiently-high energy densities, this medium would be in the Quark-Gluon Plasma phase. Afterwards, as the expansion reduces the energy density, the system goes through a hadron gas phase and finally reaches the freeze-out, when the final state hadrons do not interact with each other anymore.

2. – Evidence for deconfinement in heavy-ion collisions: the SPS programme

The desire to test this fascinating phase structure of strongly-interacting matter led, in the 1990s, to the fixed-target experiments at the AGS in Brookhaven (Au-Au $\sqrt{s_{NN}} \simeq 5$ GeV) and at the CERN-SPS (Pb-Pb $\sqrt{s_{NN}} \simeq 17$ GeV).

The energy density reached in central Pb-Pb collisions at the SPS was estimated (from the measured transverse energy of the produced particles [4, 5]) to be $\varepsilon \approx 3 \text{ GeV/fm}^3$, *i.e.* above the critical value ε_c . The two clearest indications for the production of a deconfined medium in Pb-Pb collisions at the SPS are:

- the enhancement of the production of strange and multi-strange baryons (hyperons) with respect to the rates extrapolated from pp data (predicted by J. Rafelski and B. Müller in 1982 [6]);

⁽¹⁾ In a pion gas the degrees of freedom are only the 3 values of the isospin for π^+ , π^0 , π^- . In a QGP with 2 quark flavours the degrees of freedom are $n_g + 7/8 (n_q + n_{\bar{q}}) = N_g(8) N_{\text{pol}}(2) + 7/8 \times 2 \times N_{\text{flav}}(2) N_{\text{col}}(3) N_{\text{spin}}(2) = 37$. The factor 7/8 accounts for the difference between Bose-Einstein (gluons) and Fermi-Dirac (quarks) statistics.

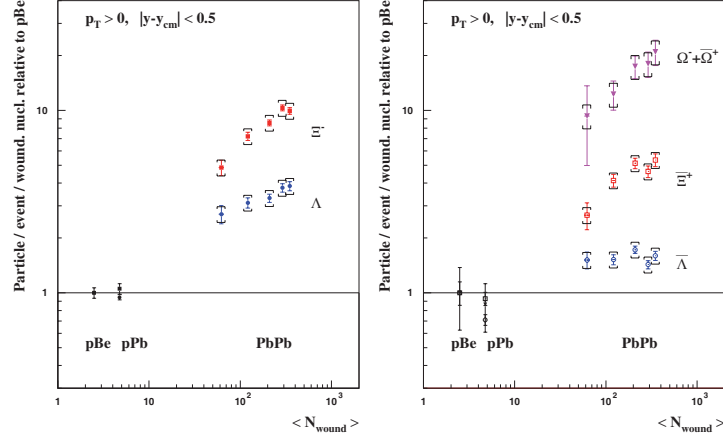


Fig. 2. – Strange baryon production in Pb-Pb per participant nucleon, normalized to the ratio from p-Be, as a function of the number of participant nucleons, as measured by NA57 at the SPS [7].

- the suppression of the production of the J/ψ meson (the lowest $c\bar{c}$ bound state), always with respect to the rates extrapolated from pp (predicted by T. Matsui and H. Satz in 1986 [8]).

In the QGP, the chiral symmetry restoration decreases the threshold for the production of a $s\bar{s}$ pair from twice the constituent mass of the s quark, ≈ 600 MeV, to twice the *bare* mass of the s quark, ≈ 300 MeV, which is less than half of the energy required to produce strange particles in hadronic interactions. In the QGP, multi-strange baryons can be produced by statistical combination of strange (and non-strange) quarks, while in a hadronic gas they have to be produced through a chain of interactions that increase the strangeness content in steps of one unit. For this reason a hyperon enhancement growing with the strangeness content was indicated as a signal for QGP formation. This effect was, indeed, observed by the WA97/NA57 experiment [7]: in fig. 2 one can see that the production of strange and multi-strange baryons increases by 10 times and more (up to 20 times for the Ω) in central Pb-Pb collisions in comparison to p-Be, where the QGP is not expected. As predicted, the enhancement \mathcal{E} is increasing with the strangeness content: $\mathcal{E}(\Lambda) < \mathcal{E}(\Xi) < \mathcal{E}(\Omega)$.

The other historic predicted signal of deconfinement was observed by the NA50 and NA60 experiments (in Pb-Pb and In-In collisions, respectively): the suppression of the J/ψ particle yield, with respect to the reference Drell-Yan process [9,10]. The suppression is interpreted as due to the fact that, in the high colour-charge density environment of a QGP, the strong interaction between the two quarks of the $c\bar{c}$ pair is screened and the formation of their bound state is consequently prevented.

3. – RHIC: focus on new observables

The Relativistic Heavy Ion Collider (RHIC) in Brookhaven began operation during summer 2000. With a factor 10 increase in the centre-of-mass energy with respect to the SPS, $\sqrt{s_{NN}}$ up to 200 GeV, the produced collisions are expected to be well above the phase transition threshold. Moreover, in this energy regime, the so-called “hard processes” —production of energetic partons ($E > 3\text{--}5$ GeV) out of the inelastic scattering

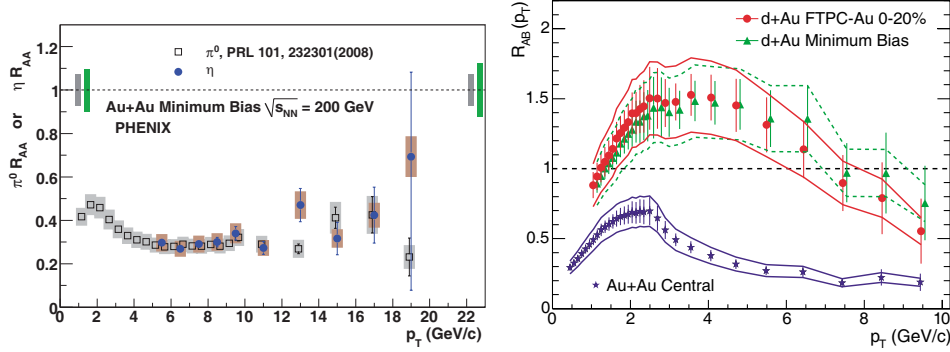


Fig. 3. – The ratio of transverse-momentum distributions of hadrons in Au-Au collisions and pp collisions, scaled by the number of binary nucleon-nucleon collisions at $\sqrt{s_{NN}} = 200$ GeV. Left: PHENIX data for π^0 and η [18]. Right: STAR data for charged hadrons [19]; also the ratio d-Au to pp is shown.

of two partons from the colliding nuclei— have a significantly large cross section and they become experimentally accessible.

In this scenario, beyond the “traditional” observables we have already introduced, the interesting phenomenon of in-medium parton energy loss [11-13], predicted for the first time by J. D. Bjorken in 1982 [11], can be addressed.

Hard partons are produced at the early stage of the collision and they propagate through the medium formed in the collision. During this propagation they undergo interactions (both inelastic and elastic) with the gluons present in the medium and they lose energy. Such energy loss is not peculiar of a deconfined medium, but, quantitatively, it is strongly dependent on the nature and on the properties of the medium, being predicted to be much larger in the case of deconfinement.

The measurement of high- p_T (projection of the momentum on the plane transverse to the beam line) particle production has been addressed at RHIC mainly by the PHENIX [14] and STAR [15] experiments, but has been observed also by the two smaller experiments BRAHMS [16] and PHOBOS [17]. The results are striking. Figure 3 reports the yield of neutral and charged hadrons measured by PHENIX [18] and STAR [19] in central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV, divided by the yield in pp collisions at the same energy and by the estimated number of binary nucleon-nucleon collisions. This ratio, R_{AA} , should be one at high p_T if no medium effects are present. In central collisions the yield is reduced of a factor 4–5 with respect to what expected for incoherent production in nucleon-nucleon collisions.

Another impressive result, obtained by STAR and PHENIX, is the disappearance of the back-to-back azimuthal correlations of high- p_T particles in central Au-Au collisions. In fig. 4 the azimuthal correlations of charged particles with respect to a high- p_T trigger particle (star markers) in central Au-Au are shown and compared with reference data from pp collisions (histogram): in central collisions the opposite-side ($\Delta\phi = \pm\pi$) correlation is strongly suppressed with respect to the pp and peripheral Au-Au cases. This effect suggests the absorption of one of the two jets (usually produced as back-to-back pairs) in the hot matter formed in central collisions.

The effects of leading particle and jet suppression are not observed in d-Au (deuteron-gold) collisions at $\sqrt{s_{NN}} = 200$ GeV (circle and triangle marks in figs. 3-right and 4), where the formation of a dense medium is not expected.

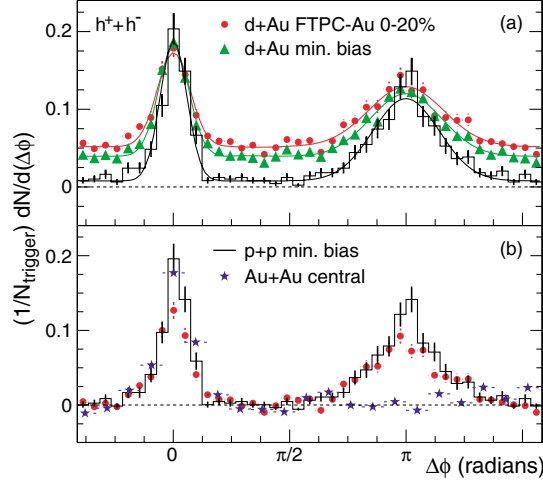


Fig. 4. – Azimuthal correlations of charged particles relative to a high- p_t trigger particle for central Au-Au, compared to d-Au and pp collisions at $\sqrt{s_{NN}} = 200$ GeV [19].

In summary, experiments at RHIC have shown that a very dense QCD medium is formed in high-energy heavy-ion collisions. Other measurements, namely elliptic flow and baryon-to-meson ratios, indicate that this medium is characterized by partonic degrees of freedom and that its expansion and cooling is well described by hydrodynamical models with high viscosity. Thus, this medium is more similar to a liquid than to a gas of gluons and quarks.

4. – LHC: study of “deeply deconfined” matter

The Large Hadron Collider (LHC) started operation with pp collisions at $\sqrt{s} = 900$ GeV (2009) and 7 TeV (since March 2010). The first Pb-Pb run, at $\sqrt{s_{NN}} = 2.75$ TeV, is scheduled for November 2010. The maximum Pb-Pb energy of 5.5 TeV should be reached in 2013. LHC will provide nuclear collisions at a centre-of-mass energy 15–30 times higher than at RHIC, opening a new era for the field, in which particle production will be dominated by hard processes, and the energy densities will possibly be high enough to treat the generated Quark-Gluon Plasma as an ideal gas. These qualitatively new features will allow to address the task of the LHC heavy ion program: a *systematic study of the properties of the Quark-Gluon Plasma state*.

Table I presents a comparison of expected values for the most relevant parameters for SPS, RHIC and LHC energies [20]. At the LHC, the high energy in the collision centre of mass is expected to determine a large energy density and an initial temperature at least a factor 2 larger than at RHIC. This high initial temperature extends also the lifetime and the volume of the deconfined medium, since it has to expand while cooling down to the freeze-out temperature, which is ≈ 170 MeV (it is independent of \sqrt{s} , above the SPS energy). In addition, the large expected number of gluons favours energy and momentum exchanges, thus considerably reducing the time needed for the thermal equilibration of the medium. To summarize, the LHC will produce *hotter, larger and longer-living* “drops” of QCD plasma than the previous heavy-ion facilities.

TABLE I. – *Comparison of the parameters characterizing central nucleus-nucleus collisions at different energy regimes [20].*

Parameter		SPS	RHIC	LHC
$\sqrt{s_{NN}}$	[GeV]	17	200	2750–5500
dN_{gluons}/dy		$\simeq 450$	$\simeq 1200$	$\simeq 5000$
dN_{ch}/dy		400	650	$\simeq 2000\text{--}3000$
Initial temperature	[MeV]	200	350	> 600
Energy density	[GeV/fm ³]	3	25	120
Freeze-out volume	[fm ³]	few 10 ³	few 10 ⁴	few 10 ⁵
Lifetime	[fm/c]	< 2	2–4	> 10

The key advantage in this new “deep deconfinement” scenario is that the Quark-Gluon Plasma studied by the LHC experiments will be much more similar to the Quark-Gluon Plasma that can be investigated from a theoretical point of view by means of lattice QCD.

Heavy-ion collisions at the LHC access not only a quantitatively different regime of much higher energy density but also a qualitatively new regime, mainly because:

- *High-density parton distributions* are expected to dominate particle production. The number of low-energy partons (mainly gluons) in the two colliding nuclei is, therefore, expected to be so large as to produce a significant initial-state saturation that would be the dominant effect governing the bulk particle production.
- *Hard processes* should contribute significantly to the total nucleus-nucleus cross-section. The hard probes are at the LHC an ideal experimental tool for a detailed characterization of the QGP medium.

Three experiments will study Pb-Pb collisions at the LHC: ALICE (the dedicated heavy-ion experiment), ATLAS, and CMS. Their excellent detector capabilities, with many complementary features, will allow to pursue an exciting heavy-ion physics program. As mentioned before, the goal of this program is a systematic study of the properties of the QGP state. In detail:

- Energy density of the hot and dense system produced in the collision, via measurement of the charged-particle multiplicity and charged-particle rapidity density.
- Temperature and baryon density of the system at the chemical freeze-out and temperature at the kinetic freeze-out, via measurement of identified-particle yields (probe chemical freeze-out) and momentum spectra (probe kinetic freeze-out).
- Hadronization mechanism of the system: interplay between quark recombination from a partonic medium and parton fragmentation outside the medium, via measurement of the baryon-to-meson ratios as a function of momentum and rapidity.
- Size of the hot particle-emitting source, via Bose-Einstein interferometry with identical bosons.

- Pressure-driven expansion of the system, to be compared to hydrodynamical models, via measurement of radial flow and elliptic flow (azimuthal particle production anisotropy in non-central collisions).
- Fluctuations induced by the QCD phase transition, via measurement of event-by-event particle spectra
- Effect of parton energy loss on heavy quarks (charm and beauty): dependence of energy loss on the parton colour charge (c quarks *vs.* gluons) and on the parton mass (b quarks *vs.* c quarks), via measurement of transverse momentum spectra of D and B mesons.
- Effect of parton energy loss on jet structure and jet fragmentation function, via measurement of reconstructed jets and photon-tagged jets (provide initial jet energy calibration).
- Quarkonium states (J/ψ , ψ' , Υ , Υ' , Υ'') suppression pattern by temperature-dependent dissociation due to colour screening in a deconfined medium, via measurement of charmonium and bottomonium yields.
- Initial temperature of the QGP (which would radiate thermal photons), via measurement of the transverse momentum spectrum of single photons.

5. – Conclusions

High-energy heavy-ion physics addresses the limits of colour confinement and the properties of QCD in extended high-density systems.

Experiments at the SPS and RHIC accelerators have provided indications on the properties of the medium formed in the collisions: the medium is deconfined, partonic, dense, and hydrodynamic.

The LHC machine and experiments will bring a big step forward in the exploration of these new territories of QCD, because the medium will be hotter and denser, because the probes for its characterization will be abundantly available, and because the new generation detectors will provide unprecedented experimental performance.

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The author thanks the Organizers of the IFAE2010 Conference for the kind invitation.

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